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Pressure cylinders under fire condition☆

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Summary The presence of pressure cylinders under fire conditions significantly increases the risk rate for the intervening persons. It is considerably problematic to predict the pressure cylinders behaviour during heat exposition, its destruction progress and possible following explosion of the produced air—gas mixture because pressure cylinders and its environment generate a highly complicated dynamic system during an uncontrolled destruction. The large scale tests carried out by the Pilsen Fire and Rescue Department and the Rapid Response Unit of the Czech Republic Police in October 2012 and in May 2014 in the Military area Brdy and in the area of the former Lachema factory in Kaznějov had several objectives, namely, to record, qualify and quantify some of the aspects of an uncontrolled heat destruction procedure of an exposed pressure cylinder in an enclosed space and to qualify and describe the process of a controlled destruction of a pressure cylinder by shooting through it including basic tactical concepts. The article describes the experiments that were carried out.

Introduction

In October 2012 and in May 2014 there was a joint project carried out by the Pilsen Region Fire and Rescue Department and the Czech Republic Police Special Forces in the Military Area Jince, or to be precise, in a former factory in Kaznějov. Large scale tests were performed in the frame of the above mentioned. There were several objectives there:

- to record, qualify and quantify some of the aspects of an uncontrolled destruction procedure of a heated pressure cylinder,
- to compare the processes of an uncontrolled and controlled destruction via shooting in the outdoors and in an enclosed space,
- to qualify and describe the shooting down process including basic tactical concepts (Hora, 2014).

To date, most scientific theses have been concerned with the explosion of pressure cylinders in the open air. Data from indoor experiments is either not available or completely absent. The article describes the tests executed; it especially focuses on the measurement methods used, the buildings which were loaded by explosion and

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their construction, basic features of the exploding pressure cylinder behavior in case of its exposition to heat, including a mention of some values obtained etc. In the conclusion, attention is paid to the basic tactics of successful controlled indoor and outdoor pressure cylinder destruction.

Military area Jince 2012

In 2011 a truck accident occurred at the 78th km of the highway D5 near Plzen in the Czech Republic, see Fig. 1. The truck transporting pressure cylinders overturned after leaving the highway tunnel and its load fell completely off. There was an acetylene leakage because the valves of the acetylene cylinders were damaged. The leaking gas was ignited by the sparks caused by the friction of metal and resinous surface of the road. In the fire condition, some of the cylinders exposed to heat began exploding. During the fire-fighting intervention the possibility to eliminate hazard of more explosions by shooting through other cylinders was evaluated. But in the end the officer in charge did not make the decision to shoot the cylinders. The intervention was later analysed. The analysis leads to two important conclusions. Firstly, the firefighters had not been able to imagine the intensity of the blast effects and the size of the affected area. Secondly, the officer in charge did not make a decision in respect to the shooting of the cylinders because of lack of knowledge and experience with this kind of controlled destruction of pressure cylinders. No doubt, had he decided appropriately, the risk would have been decreased.

Based on the above-mentioned, a complex of measures was introduced. One of them was carrying out a joint training of the Pilsen Region Fire and Rescue Department and the Czech Republic Police Special Forces focused on pressure bottles shooting tactics at the artillery shooting range in the Military Area Jince on 30th and 31st October 2012. The following goals were set down:

- find a tactical a technical frame for deploying a sniper when pressure cylinders shooting would be necessary,
- describe theoretically and demonstrate in practice the basic principles of ballistics and ballistic protection of the intervening persons, describe theoretically and demonstrate conditions of pressure bottle shooting including measures focusing on intervention management for the safety and security of the joint forces, and for risk elimination,
- acquire necessary knowledge and experience for successful and safe intervention when pressure cylinders on fire are present,
- describe theoretically and demonstrate the destruction of heat exposed cylinders and compare its rupture with an example of uncontrolled and controlled destruction of cylinders via shooting (Hora, 2014) (Figs. 2—6).

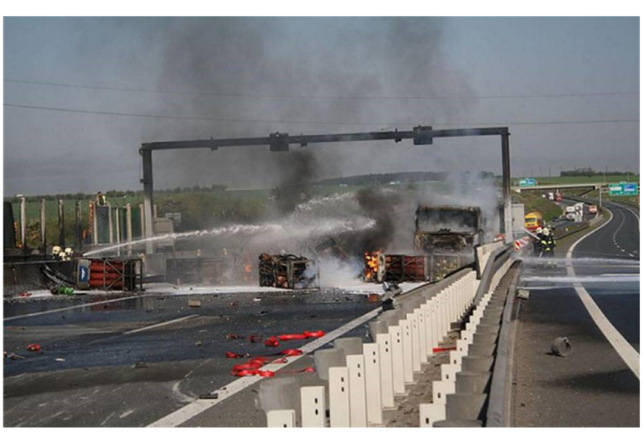

Figure 1 The situation after the traffic accident on the highway D5 during the fire and rescue service intervention.

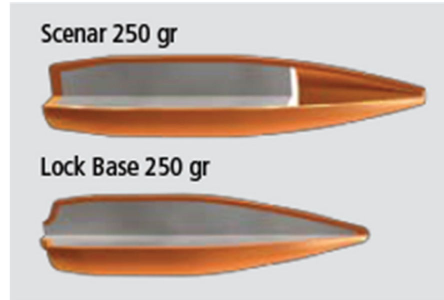

Figure 2 As an optimal ammunition 0.338 Lapua Magnum HPBT, 250 gr was chosen.

Figures 3 and 4 The situation when the calibre was too large, bullet excessively heavy, and/or ammunition overly effective. In other words, when the parameters of weapon and ammunition were not sufficient.

First of all, there were some ammunition and arm tests performed on the pressure cylinders without content in order to figure out the right technical specification. The demands mentioned bellows were stipulated:

- both firearm and ammunition must be commonly used by police corpses,
- when the visibility is good sufficient accuracy for at least 300-m distance must be guaranteed,
- when the visibility is good successful penetration of pressure cylinder surface over the distance of at least 300 m must be guaranteed,

Figures 5 and 6 When the weapons and ammunition are appropriately chosen, the bullet stops inside the cylinder because of its fragmentation.

- the bullet must be stopped inside the cylinder after passing the near wall, fragments must not be formed.

All the defined requirements for high-pressure drawn cylinders were fulfilled. In case of the welded low-pressure cylinders for liquefied gas appropriate ammunition was not found because the bullet exits the pressure bottle in all trials.

After the verification of weapons and ammunition it was possible to perform shooting of the pressure cylinders with real content consisting of hazardous material. The next tests were aimed at terminal ballistic examination in dependence on whether the pressure cylinder was empty or full and demonstration of the differences between uncontrolled and controlled destruction of the pressure bottle. Four basic kinds of possible pressure cylinder fillings were chosen: nonflammable compressed gas, flammable compressed gas, liquefied flammable gas and dissolved flammable gas. As the exponents of the above-mentioned kind of content oxygen, hydrogen, liquefied propane and acetylene were picked out, see Table 1.

The pressure bottles were arranged in rows to create a chessboard pattern:

- 4 pieces — oxygen
- 4 pieces — acetylene
- 2 pieces — propane
- 4 pieces — hydrogen (Hora, 2014).

The cylinders were placed into a bonfire and stabilised through binding to a wooden stake. The bonfire came up to 4/5 of the bottle height. At the bottom of the bonfire a 400 mm thick sawdust layer was made. The sawdust was flooded by 5 L of the mixture of motor oil and diesel in a mixture ratio 1 to 4 (Kratochvíl and Navarová, 2006; Chmel et al., 2009). The bonfire was ignited by means of black powder and an electric blasting cap. The pressure bottle destruction under fire condition was observed. Observing posts for 30 people, from which participants could observe the course of tests, were built at the distance of 50 m from the first row of cylinders. A sniper position was set up at the distance of 200 m, see Fig. 7.

Table 1 The types and numbers of cylinders tested 14th and 15th May 2014.

Number	Structure, water volume, filling pressure	Type and mass of the gas	Character of the gas
8	High pressure, drawn; 30; 2 MPa	Oxygen, 14.44	Nonflammable, pressed
8	High pressure, drawn; 30	Hydrogen	Flammable, pressed
8	High pressure, drawn; 30; 1.9 MPa	Acetylene, 15.6	Flammable, dissolved
4	Low pressure, welded	Propane 33 kg/2 kg	Flammable, liquefied

On the basis of the carried out tests several conclusions could be drawn. A significant difference in quality between uncontrolled destruction and controlled destruction via shooting was observed (Figs. 8 and 9). Later, when high-speed camera records were closely examined, it was clearly perceptible that the response of pressure cylinder to the impact of projectile was closely related to the pressure bottle content. Moreover, intense fragmentation was perceived when oxygen or hydrogen cylinders were blowing up, e.g. a lot of primary fragments were formed. Unlike oxygen and hydrogen pressure bottles, the cylinders filled with liquefied propane or acetylene formed two or three big primary fragments during the destruction (Denkstein and Kusák, 1995).

There were plenty of secondary fragments formed regardless of the construction of the cylinder or material inside the bottle during the explosion.

Based on observations made, the dimensions of the blast effect zones in the open area could be specified:

- convection — 20 m,
- radiation — 40 m,
- acoustic wave — 70 m,
- fragmentation — 200 m (Baker et al., 1983; Chmel et al., 2009).

Contrary to the original assumption, the dramatic progression of an uncontrolled destruction of the cylinders with oxygen was remarkable. This process was connected with the formation of many small primary fragments (Fig. 10). In addition to the above-mentioned, the violent reactive movement of the oxygen pressure bottle when stricken by a bullet was a surprise.

The bullet was deformed and some changes in the structure of the steel took place after the impact on the pressure cylinder surface. This process is caused by temperatures

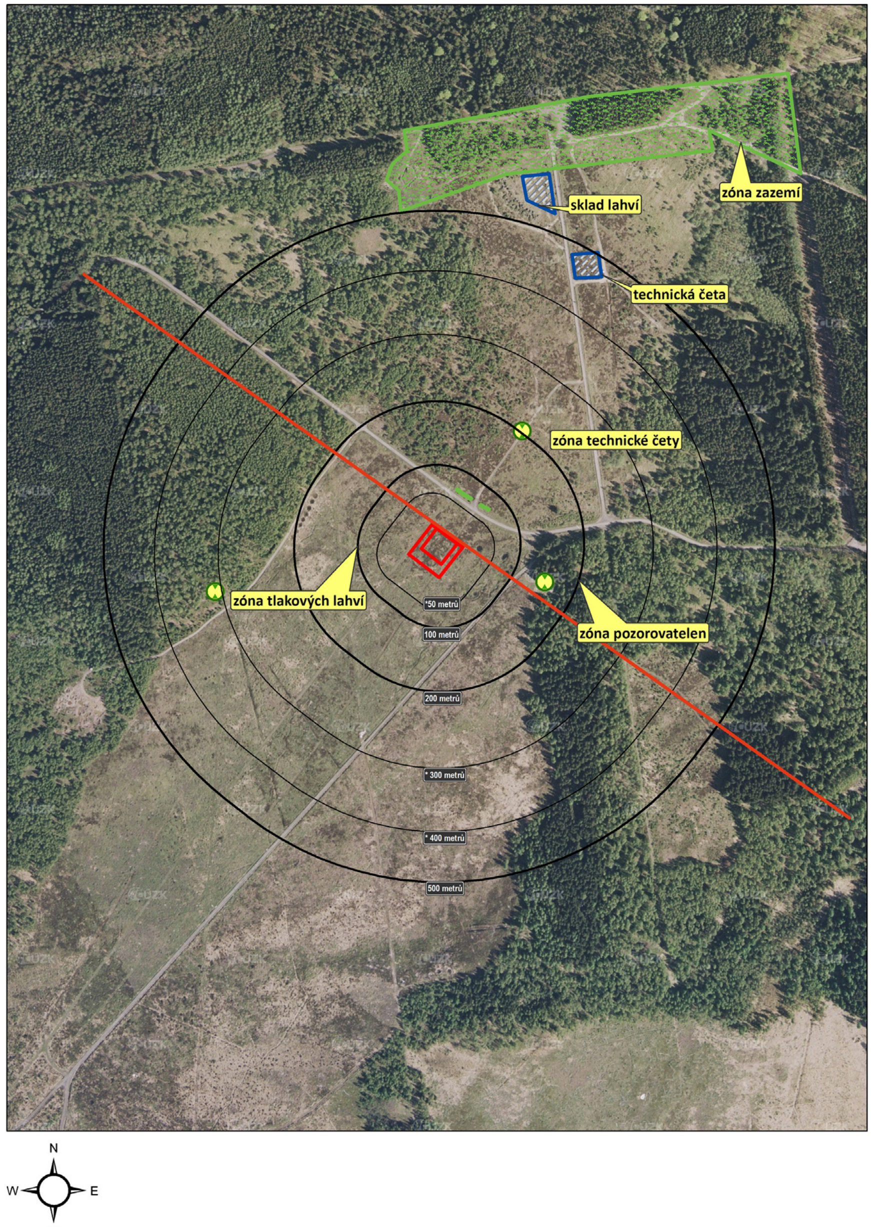

Figure 7 Arrangement of the testing area.

higher then 1550 °C when a shooting cavity arises. The shooting cavity becomes an opening through which the overpressurised oxygen is ventilated. In the atmosphere of high density oxygen the shooting cavity wall melts due to violent oxidation. A ten times wider hole then the original diameter of the projectile is the result of this process (Fig. 11).

An interesting example of BLEVE as a result of an uncontrolled destruction of a low-pressure welding cylinder with propane was seen on the first day of tests. The mechanical explosion had been so strong that a 25 kg heavy fragment was found in the distance of over 160 m. As a consequence of cold weather (it was 4 °C), and high humidity, the propane mists arising due to a violent leakage after the rupture of the pressure bottle was not ignited (Fig. 12). This mixture of propane droplets, gaseous propane and air is considerably hardly ignitable under the conditions mentioned above because of the matter being unequally distributed in the mixture, a narrow explosion limit and high minimum ignition energy (Baker et al., 1983; Drysdale, 1998; Quantiere, 1997). Moreover, the ignition energy must affect quite large area of arisen cloud in order to start an exothermic run-away reaction (Janovský, 2004). In general, the process of propane mist ignition is heavily heat consuming. The compact and heavy cloud of propane mist had passed the distance of 70 m copying the terrain before dissipating.

Based on the experiments performed a wide discussion begun. Among other findings, the conclusion to carry out the same tests in an enclosed space was formulated.

Figure 8 A controlled destruction of a high pressure drawn cylinder via shooting. The cylinder in the picture contained acetylene.

Figure 9 An uncontrolled destruction of a high pressure drawn cylinder. The cylinder in the picture contained acetylene.

The grounds of the former factory Lachema in Kaznejov, 2014

The continuation of the previous tests, where about of the behavior of the cylinders exposed to heat outdoor, was realised in the former factory Lachema in Kaznejov in May 2014. These tests were combined with common practice of The Pilsen Region Fire and Rescue Service and Police Special Forces. Targets were defined:

- to verify and adjust the suggested technical and tactical procedures for sniper deploying intervention in case of fire in the interior space with the presence of cylinders,
- to acquire basic skills for effective and safe intervention in a fire involving cylinders, to demonstrate process and effects of the uncontrolled destruction of cylinders with different gas and also demonstrate the process of destruction of cylinders depending on the method of handling before fire,
- to acquire practical experience with the behavior of pyrophoric mixture, demonstrate process of its auto-initiation,

Figure 10 The fragmentation of a high pressure drawn cylinder. The cylinder in the picture contained oxygen.

Figure 11 The penetration of a high pressure drawn cylinder. The cylinder in the picture contained oxygen.

Figure 12 The situation after BLEVE. A flying large fragment is clearly visible.

- to measure explosion parameters for different types of the structure and content of the cylinders,
- to demonstrate and evaluate explosions of cylinders with different structure and content, including the response of the building construction,
- to describe and demonstrate the basic tactical procedures and principles of cooperation IRS (Integrated Rescue

Figure 13 The situation after a controlled destruction of a low pressure welded cylinder. The cylinders in the picture contained liquefied propane.

Figure 14 The situation after an uncontrolled destruction of a high pressure drawn cylinder. The cylinders in the picture contained hydrogen. A tendency to fragment is obvious.

Table 2 The types and numbers of cylinders tested 14th and 15th May 2014.

Number	Structure, water volume, filling pressure	Type and mass of the gas	Character of the gas
13	High pressure, drawn; 30; 2 MPa	Oxygen, 14.44	Nonflammable, pressed
1	High pressure, drawn; 30	Hydrogen	Flammable, pressed
15	High pressure, drawn; 30; 1.9 MPa	Acetylene, 15.6	Flammable, dissolved
10	Low pressure, welded	Propane 33 kg/2 kg	Flammable, liquefied

System) components, and also to describe and demonstrate synergy, coordination, organisation and management of IRS components during rescue work at the risk of explosion of cylinders (Hora, 2014).

The requirements of the experiments realised with the cylinders with real content in interior space were the same as for testing outdoors, see above. Technical gases used for the experiments are most common and most acceptable and also represent the basic types of filling of cylinders: compressed non-combustible, compressed flammable gas, liquefied gas and dissolved gas — the numbers of cylinders are shown in Table 2. Based on the performed tests it should be possible to assess qualitatively and describe the behavior of cylinders from the view of terminal ballistics, which includes its structure and content, and to describe the uncontrolled destruction of the cylinders in the interior space, respectively to compare sniper's activity during an intervention in an enclosed space with his activity during the intervention outdoors.

Figure 15 The situation after a controlled destruction of cylinders. The cylinders in the picture contained hydrogen.

A description of the object

The object of former fermentation in the area of the former factory LACHEMA in Kaznejov was chosen for the tests. Originally it was continuously working operation. The building had several parts, but some parts were torn down. Input part had 7 floors and reactors were placed here originally. Individual floors were connected with double staircase and elevator shaft. The access to the entire object was from this part. The siding was conducted in longitudinal tract through the entire building and through the hall to the rear, where the rear wall formed a peripheral structure of the whole object. These cubicles rattled to the corridor siding. In the second floor there were empty spaces connected with the technological passages in the first floor. Technological part which had three floors followed the entrance part in the transversal direction. The overall location and views on the parts of the objects, in which the experiment was carried out, is shown in Figs. 13—20.

Reinforced concrete column system with reinforced concrete beams formed the building structure, partially formed by reinforced columns and partially formed by vertical construction made of full bricks, bricked by lime mortar with a width of 900 mm. The columns bricked by full bricks were

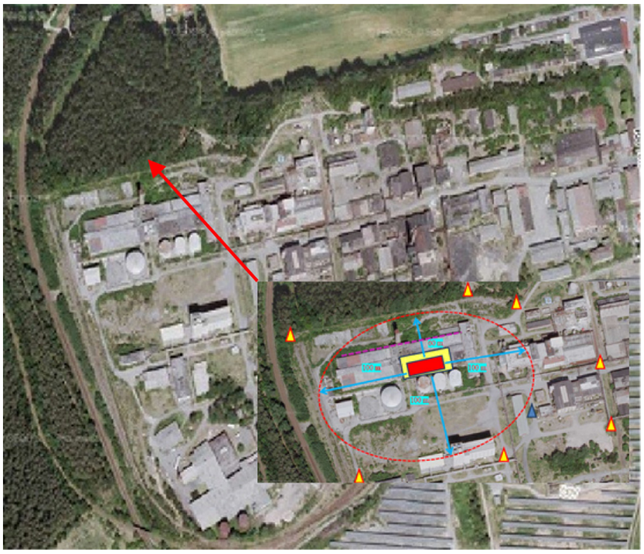

Figure 16 The overall view of the area of the former Lachema factory in Kaznejov and the detail of the former fermentation building with the indication of the security perimeter.

Figure 17 View of the building of the former fermentation where experiments took place. The places where the cylinders were located are marked by arrows.

Figure 18 The siding corridor and individual cubicles. The dimensions of a cubicle were (7 × 13) m. The height of the ceiling was 6 m.

Figure 19 An enclosed room in the technological part where parameters were measured during the explosion of the pressure cylinder with acetylene. The dimensions of the room were (14 × 13) m, the ceiling height was 3 m and 4.2 m.

Figure 20 The staircase where a controlled destruction took place. The dimensions of the staircase were (2.9 × 5) m, the height 21.3 m.

in the part where the cubicles were. The vertical constructions without the support function were formed by full bricks bricked by lime mortar with width of 300 mm and 400 mm, respectively. The ceiling was formed by reinforced concrete slab with reinforced concrete beams. Ribbed ceiling was installed in some places. The wall where the detectors were installed was doubled. In the window openings there were the windows with glass filling or glass panels. The rear wall separated the room from the hall orientated in longitudinal tract, the rear wall of the hall formed peripheral construction of the whole object. The floor was formed by reinforced concrete slab.

The cylinders were placed along the longitudinal axis of the room and subsequently enclosed around by woodpile made of spruce timber prisms (100 mm × 100 mm × 900 mm), or from the corresponding dry logs in an amount equal to 4/5 of the height of the cylinder. The wood was weighed and the weight was marked on the wall of the experimental room. The layer of sawdust (of a 400 mm thickness) was placed at

Table 3 Location of the cylinders in the test spaces.

Floor	Room	ACT	H_2	PRP 33/2	O_2	The way of destruction		
2nd floor	Big	1	1			UD-M		
1st floor	Big				4	CD		
1st floor	Cubicle	4		4/0	1	CD, UD		
1st floor	Corridor				1	UD		
1st–3rd floor	Staircase	10		4/2	7	CD		
	Total	15	1	4/2	13	CD		

CD — controlled destruction, UD — uncontrolled destruction, UD-M — uncontrolled destruction with the measurement, blue colour — without the presence of a flame, red colour — with the presence of a flame.

the bottom of the woodpile and subsequently covered by 5 l of used motor oil and diesel mixture in the ratio 1:4 kg (Chmel et al., 2009; Kratochvíl and Navarová, 2006). The woodpile was ignited by black dust, initiated by an electrical igniter. The location of the cylinders is shown in Table 3.

The hazard of initiation failure during uncontrolled destruction of the cylinder with propane was assessed like the probable hazard during the planning of the experiment. Therefore two tin baths sized (1.5×1) m were installed in the corridor of siding. The cylinders were located between them, so the closer bath was not further than 12 m. The baths were filled with wood and cast by a mixture of used oil and diesel. This backup source of initiation was ignited at a distance, 3 min later after the ignition of the pile with the cylinder.

Another problem, which was needed to solve urgently, was the possibility that the cylinder will not be destruct according to the plan and the gas will not leak through the valve. This was the reason, why the openings in the wall were cut out in a way that the cylinder would be shot through the openings in the wall (Hora, 2014). Although in one case it was impossible and the cylinder, where the runaway reaction was started, was torn after 57 min from the initiation of the pile.

The parameters measurement during explosion of cylinder with acetylene

During the test, the staff of The Fire Technical Institute in Prague and the staff of VŠB — Technical University of Ostrava, Faculty of safety engineering monitored several parameters:

- temperature profile on the surface of the cylinders by using four thermocouples,
- the pressure inside the cylinder during the heating,
- the temperature field inside the room,
- the measurement of the pressure in the wall perpendicular to the cylinder at a height of 1.5 m and 2.5 m.

The temperature field was measured by thermocouples type K by using ALMEMO central for data collection.

The measurements of the pressure were realised with pressure sensors KISTLER, type 701A, with data collection by using central Dewetron with the scanning frequency 100 kHz. The pressure sensors were placed at a height of 1.5 m and 2.5 m on the perpendicular to the closest wall.

Figure 21 Deflagration of the air mixture with acetylene.

Figure 22 The fragmentation during the explosion of cylinders with acetylene.

Uncontrolled destruction of cylinders with acetylene occurred at about 7 min after igniting the woodpile with an electric igniter (see Figs. 21—23). The rupture that occurred in the cylinders, was throughout its length, see Fig. 24.

The explosion of the cylinder had intensive destructive effects (documented in Figs. 25 and 26). The ceiling slab

Figure 23 The outside view of the room during the explosion of pressure cylinders with acetylene.

Figure 24 A pressure cylinder after destruction.

was lifted and partial destruction of the structures occurred in higher levels of the object, and as a consequence of it girders broke and crushed concrete spilled. The construction of the three perimeter walls of full bricks was bulging out of the room in the direction of the pressure wave.

Figure 25 The ceiling and front wall after the explosion of cylinders with acetylene-view from the outside.

Figure 26 The left side of the room after the explosion of cylinders with acetylene — view from the outside.

The wall near the openings, which decreased the effect of the explosion, maintained its integrity in one case completely, in another case partially — the wall was ripped from the joint with the ceiling structure and showed numerous cracks. The resonance of the pressure effects can be assumed at the phase of physical expansion and at the phase of its creation burning air—gas mixture, while the interference of pressure waves caused by the impact on the wall and the reflection from the wall can be assumed.

The disturbances created on the reinforced concrete girders had progressive character and led to the total loss of stability during 36 h and the consequent collapse of the part of the building with the lowered ceiling. It is necessary to think on the fact, which is typical after the action of the effects of resonating pressure waves created by explosion in an enclosed space, during the rescue and liquidation works.

The measurement results of the temperature field is shown in Fig. 27. The pressure inside the cylinder was not measured throughout the test time probably because of the failure of the pressure sensor at such high temperatures. Similarly, the loading of the shell of the cylinder and the temperature measurement was wrong. The contact of thermocouple with the flame was caused probably by the leak isolation, and therefore the measured temperatures are higher than would correspond to reality.

The results of the measurements of pressures in the wall perpendicular to the cylinder with acetylene are shown in Fig. 28. In the graph you can see the resonance of active element of sensors, called ''ringing'' of sensors, which significantly distorted the measurements. Therefore the real values and character of load can only be estimated. It may be assumed that the pressure reached maximal values about 2500 Pa and the load due to the time of action fell within the transition region between pulse and quasi load.

Uneven action of the pressure wave probably caused the disorders of the wall. The wall is damaged on the edges. This illustrates the propagation of the pressure wall along the side walls later than the middle of the room. The pressure wave propagating in the middle of the room was also reflect to the sides, where its effect was summed with the effect of the pressure wave propagating from along the side walls

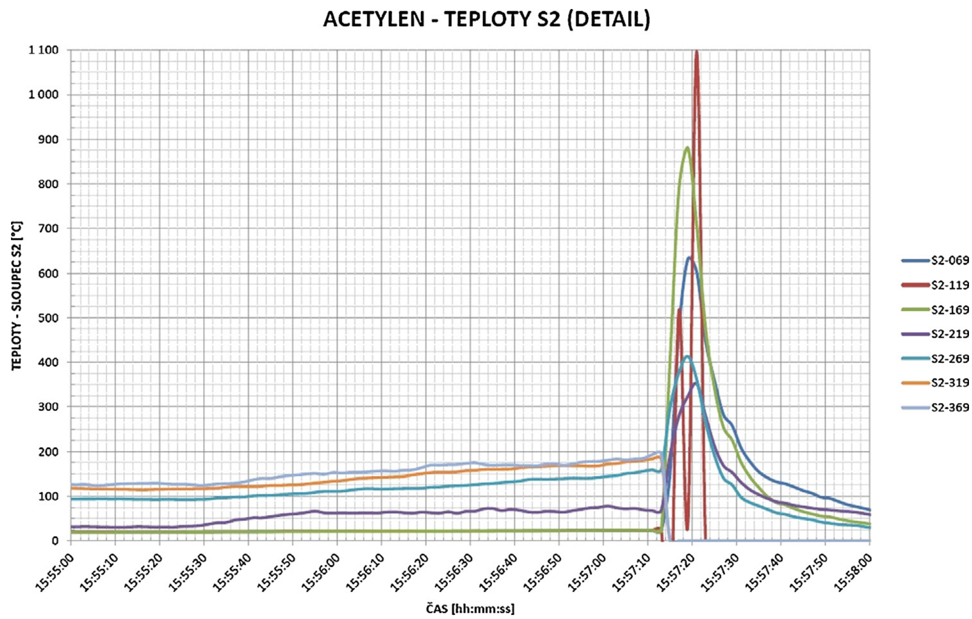

Figure 27 The results of the measurements of the temperature field on the column S2.

with a certain time delay. The sum of the pressure effects became in the place of the conflict of pressure waves at the edge of the visible wall and consequently led to the buckling out of the closed space. The fragmentation image on the floor in the middle of the room confirmed the slight implosion in this place.

A qualitative description of the destruction of cylinders with acetylene and propane

The aim of the tests was a description of the explosion caused by structural failure of cylinders during the uncontrolled destruction of 4 cylinders with acetylene and 4 cylinders with liquid propane. The cylinders were placed in the cubicles leading into the corridor of siding. The cubicles were optimal for planning observation because of similar type design spaces and it was possible to partially compare different character of changes on similar structures. The cubicles were not separated from the corridor of siding by building construction and the common wall formed a single exhaust area. As a consequence it could be presumed that the progress of the explosion of the cylinder can be easily observed and the disturbances on the structures will be sufficiently obvious, but will not cause the collapse of the part of the object.

The load caused by the explosion of the cylinder with acetylene showed impulse-static character, when the static and impulse phases were not clearly separated (Janovský, 2004). This progress seems to be associated with a wide

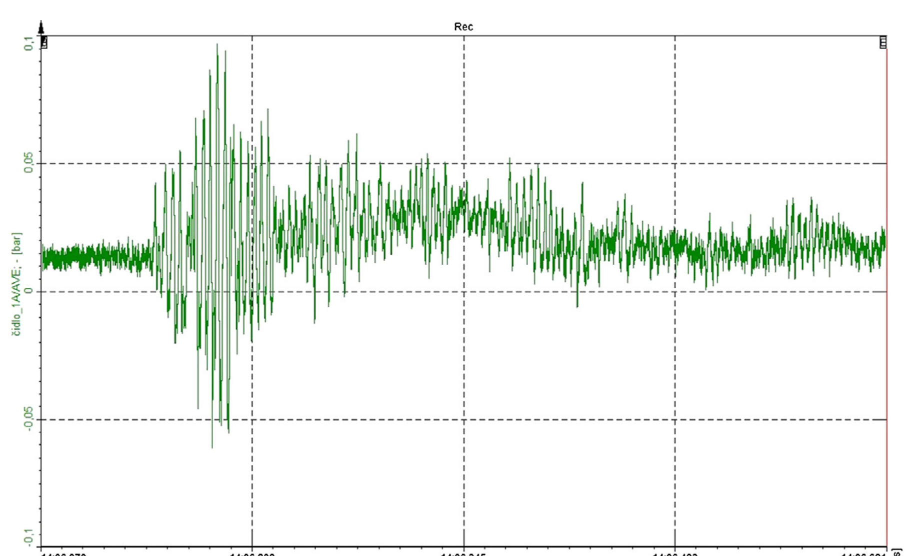

Figure 28 A record of the pressure during the destruction of cylinders at the height of 1.5 m above the floor.

Figure 29 The progress of an explosion of pressure cylinder with acetylene in one of the cubicles.

Figure 31 The process of the explosion of the pressure cylinder with acetylene in one of the cubicles in the later phase. Turbulent vortex is visible in the upper part of the corridor.

interval between explosiveness and low initial energy of the mixture acetylene-air. The mixture of acetylene with air started to burn even during the expansion of the gas after the cylinder burst, when the significant surplus of acetylene was in the mixture (The Czech Association of the Industrial Gasses). The captured records show, that the burning mixture filled as cubicle, where the cylinder was placed as the opposite cubicle and then spread through the corridor in the longitudinal direction. Then the mixture spread through the openings in the peripheral construction and ceiling construction to the second floor, respectively out of the object, where the mixture burnt out. The different speed of burnout of mixture inside and outside indicates that the combustion should not be kinetic character, but there was present a significant influence of diffusion processes (Figs. 29—31).

BLEVE occurred during the explosion of the cylinder with propane. The load caused by the explosion of the cylinders with propane had significantly discontinuous process, when the impulse phase and the static phase were clearly

Figure 30 The process of the explosion of the cylinder with acetylene in one of the cubicles in the initial phase. Expanding gas followed by the zone of combustion is evident.

separated. This process is apparently related to rapid gas expansion due to BLEVE and narrow interval between explosiveness and the high value of initial energy of the mixture propane-air. The mixture of propane and air began to burn after the expansion of propane has finished. The record from the interior shows that the pile was spreading — of its larger part — and in the atmosphere with significant excess of the propane, the interruption of the flame combustion and combustion of their remains happened. A flame of a backup source, i.e. burning oil and wood in a tin bath located at the edges of the cloud of the mixture propane-air, was the initial source. The captured records show that the burning mixture not only filled the cubicle, where the cylinder was placed, but also the opposite cubicle and then spread through the corridor in the longitudinal direction. The mixture spread through the openings in the peripheral construction and through the ceiling construction to the second floor and out, respectively. The mixture burnt out mainly by the deflagration way and the burning showed significant kinetic character. The delay in burnout of gaseous residues inside the building was also observed in this case although to a much lesser extent. It is possible to believe that the combustion had partially diffuse character in the end (Figs. 32 and 33).

Despite the fact, that the explosion was vented, some structures could not resist its effect. After the explosion of the cylinder with acetylene the peripheral construction was damaged in its upper part at a height equivalent to about half the height of the construction and in their lower parts the peripheral construction was torn from the supporting structures. A zone of debris was visible on the outer side of the object and formed a band with a width of 8 m and a length of 9 m (Fig. 34). The damage of the peripheral construction showed progressive process in a connection with the stress caused by other explosions of acetylene and LPG. However, damage showed downward trend due to the increase of the total area of the exhaust walls. The cracks

Figure 32 The process of the explosion of the cylinder with propane in one of the cubicles in the phase of expansion. The leaking propane is visible in the holes of the wall at the bottom right.

Figure 33 The process of the explosion of the cylinder with propane in the moment when the explosion reached the maximal parameters.

Figure 34 The destruction of the peripheral wall after the explosion of the cylinder with acetylene. The zone of debris is visible bellow the wall.

Figure 35 The failure of the internal supporting wall and column after the explosion of the cylinder with acetylene.

in the masonry were visible on the supporting structures that were mounted transversely at a height corresponding to approximately half of a height of the structure. A violation of a binding between the ceiling and the walls could be a possible explanation and it is due to the movement of ceiling construction upwards.

The momentum was created on the walls due to continuous load by explosion and this momentum caused cracks on the supporting walls and on the peripheral construction without the supporting function momentum caused, that the peripheral construction rolled out. The bricked columns made of full bricks slightly overhung to the room and formed a barrier against the expanding gas. These edges were knocked down by the explosion (Fig. 35). When we compare the effects of the explosion of the cylinders with acetylene and of the cylinders with propane, acetylene had a more significant effect on the structure and propane excelled in the size of the creating cloud and in the size of the combustion zone.

The process of the controlled destruction was determined by firefighter called ''Tracer'', who was located in a sheltered outpost at a distance of about 70 m from the place of visual contact with the cylinders. The firefighter near the sniper accepted the demands of ''Tracer'' and passed it to the sniper. In the reverse direction ''Tracer'' was informed about the situation on the position of the sniper about possible complications, limitations and problems. As a part of an evaluation of both large-scale tests there were determined subsequent tactical recommendations:

- the position of ''Tracer'' in a shelter, ''Tracer'' in the position before the sniper identifies the cylinders and decides about the order of their shooting through,
- the assistant of the controller in the position with the sniper passes the demands of the controller to the sniper and informs about the situation at the position of the sniper,
- the position of the sniper at a safe distance — if it is possible to use shields and protection, it is recommended to

Figure 36 The controlled destruction of the cylinder with acetylene.

deploy two to three snipers at a sufficient distance from each other — crossfire increases efficiency,

- it is suitable to shoot the cylinders in series, the order of the shooting depends on their content and position, hitting the cylinder at least twice; acetylene and liquefied gases — the first hit should be placed to the upper part above the expected level of liquid, the second hit should be placed as low as possible below the expected level of liquid; the hit for the compressed gas should be placed to the centre of the cylinder (Hora, 2014).

The determination of the order of the cylinders for the destruction should be based on the presumption of their behavior in the inner space. Acetylene showed intensive heat treatment but in a relatively small area, while the cylinder was stable (Fig. 36).

The cylinder with propane was also stable after the hit, but wide area of flame combustion with long-term heat treatment created during the controlled destruction. The cylinder with oxygen was markedly unstable after the hit and showed an intensive reactive motion. Its controlled destruction was associated with a relatively large area of flame combustion, a heat treatment was short. The mutual heat interaction between the controlled destruction of the cylinder and the surroundings of the cylinder did not represent a significant factor. A noticeable deformation showed only a thin-walled low-pressure cylinders, where the ''inflation'' of the cylinder caused by the action of internal pressure was obvious. In the case of the controlled destruction building constructions showed only signs of a thermal stress, while they completely preserved their carrying capacity and stability. In the place of the most thermal exposition an apostasy plaster locally occurred (Fig. 37). During the uncontrolled destruction for acetylene and propane there is generated a large amount of the smoke, in which a large amount of the soot is contained in the case of acetylene.

Figure 37 The situation after the controlled destruction of cylinders. The cylinders on the picture contained acetylene and oxygen. The subsiding plaster due to the heat treatment is visible in the background.

Conclusion

In spite of the high destructiveness of a blast not a lot has been done in the field of examination of the pressure cylinder explosion under fire conditions so far, especially in an enclosed and semi-enclosed space. One of the reasons could be the extremely difficult arrangement and realisation necessary to perform large scale tests. It is considerably problematic to predict the pressure cylinders behavior during heat exposition, the destruction progress and the possible following explosion of the produced air—gas mixture because the pressure cylinders and their environment generate a highly complicated dynamic system during an uncontrolled destruction. The state of its particular elements — the pressure cylinder, its content and its environment — changes all the time during the process of explosion. The change is non-linear and non-stationary. The load caused by the explosion implies a response from the environment. Simultaneously, the environment response determines the parameters of the blast.

There are several stages in the above-mentioned process. At first the rupture of cylinder occurs due to a common effect of the internal pressure increase and loss of the solidness of the steel on the body of the cylinder as a consequence of being heated up. Subsequently, the overpressurised content of the pressure bottle violently leaks. An acoustic wave is generated by the mechanical explosion. In the case of flammable gas the next stage is deflagration of air—gas mixture and sufficient source of ignition is present. This process is inharmonious, non-linear and non-stationary cylinder (Kratochvíl and Navarová, 2006; Chmel et al., 2009).

It can be stated that the benefits of these large scale experiments described above have been extraordinary for the unique character of the obtained data and large amount of video records and photos. It allows to make a qualitative description of pressure cylinder explosion in an open space or indoor including the response of the environment and to stipulate same quantitative conclusions of its aspects. Within European Union, this would be a unique and challenging project. Design and development of methods and methodology is essential including the identification of its blind spots. Regardless of the impossibility to carry out these tests in the same area and under the same conditions and the necessity to reflect the inevitability of mistakes and deviations, for both theory and practice it is necessary to continue the research as it is possible to validate and verify the obtained results when coincidence or similarity are ascertained. From this point of view it makes sense to create a group of experts which would collect practical data on the site of real events. This could be meaningful and helpful in many areas, e.g. in the creation of tactical patterns for intervention of safety and security service, in the design of technologies where a high risk is at presence, in the progress of industrial accidents investigation etc.

Conflict of interest

The authors declare that there is no conflict of interest.

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